

# REVIEW ON TOP FORWARD-BACKWARD ASYMMETRY

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The top forward-backward asymmetry (FBA) observed at the Tevatron has been a hot issue in particle physics for the last few years. In this talk, I describe two different approaches for the top FBA at the Tevatron, one in effective field theory (EFT) approach and the other in explicit model for  $Z'$ . Within the first approach, I identify a class of models which can accommodate the top FBA when new physics scale is very heavy. Axigluon or  $t$ -channel scalar exchanges with flavor dependent couplings can do the job. In the second approach, I show that the chiral couplings of  $Z'$  necessarily invites multi Higgs doublets with  $Z'$  couplings. Otherwise the top quark becomes massless, which is completely unphysical. Newly introduced multi Higgs doublets also contribute to the top FBA,  $\sigma_{tt}$  and the charge asymmetry at the LHC, and there are parameter regions which are compatible with all the observations related with the top quarks.

## 1 Introduction

The  $A_{\text{FB}}$  of the top quark is one of the interesting observables related with top quark. Within the Standard Model (SM), this asymmetry vanishes at leading order in QCD because of  $C$  symmetry. At next-to-leading order [ $O(\alpha_s^3)$ ], a nonzero  $A_{\text{FB}}$  can develop from the interference between the Born amplitude and two-gluon intermediate state, as well as the gluon bremsstrahlung and gluon-(anti)quark scattering into  $t\bar{t}$ , with the prediction  $A_{\text{FB}} \sim 0.078$ <sup>1</sup>. The measured asymmetry has been off the SM prediction by  $\sim 2\sigma$  for the last few years, albeit a large experimental uncertainties. The averages of the lepton plus jet and the dilepton channels in the  $t\bar{t}$  rest frame were reported at the ICHEP2012 by both CDF and D0 Collaborations<sup>2</sup>:

$$A_{\text{FB}} \equiv \frac{N_t(\cos \theta \geq 0) - N_{\bar{t}}(\cos \theta \geq 0)}{N_t(\cos \theta \geq 0) + N_{\bar{t}}(\cos \theta \geq 0)} = (0.201 \pm 0.067)(\text{CDF}) \quad (0.196 \pm 0.060)(\text{D0}) \quad (1)$$

with  $\theta$  being the polar angle of the top quark with respect to the incoming proton in the  $t\bar{t}$  rest frame. This  $\sim 2\sigma$  deviation stimulated some speculations on new physics scenarios. On the other hand, search for a new resonance decaying into  $t\bar{t}$  pair has been carried out at the Tevatron and the LHC. Also there is no evidence for large top charge asymmetry at the LHC<sup>2</sup>.

In this talk I describe two independent approaches for the top FBA, one in the effective field theory (EFT) approach, and the other within an explicit gauge model with  $Z'$ . In Sec. 2, I address the top FBA within the EFT framework, assuming that the new physics scale relevant to this puzzle is very heavy and does not show up at the Tevatron. In Sec. 3, we consider the  $Z'$  model, implementing it to the realistic gauge theory. We find that the original  $Z'$  model by Jung *et al.*<sup>3</sup> should be extended by introducing new Higgs doublets that couple to the  $Z'$  in order to generate nonzero masses for the up-type quarks. We show how this model with relatively light  $Z'$  can satisfy all the available data as of now. This talk is based on a series of my works<sup>4,5,6,7</sup>.

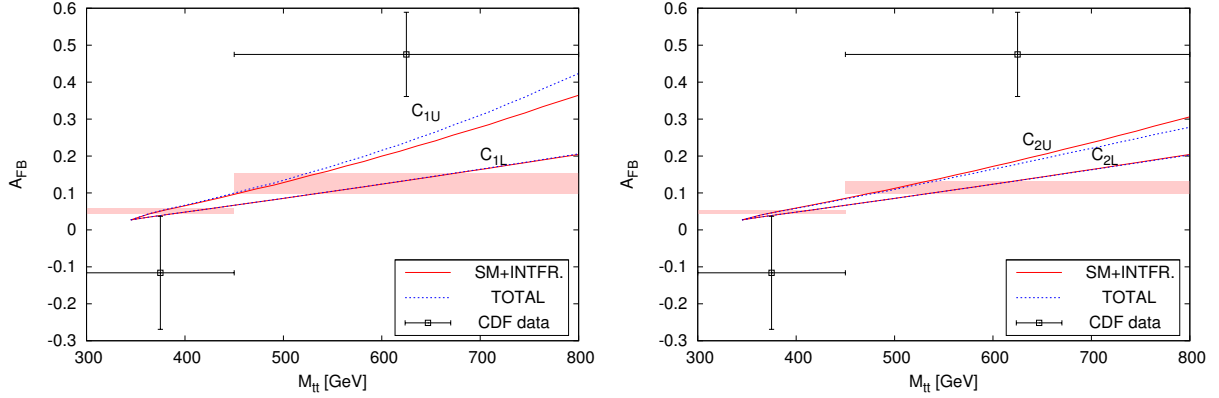


Figure 1: The  $m_{t\bar{t}}$  distributions of the top FBA for (a)  $C_2 = 0$  and (b)  $C_1 = 0$ . Blue dotted curves include the square of new physics amplitudes in addition to the interference term.

## 2 Effective Field Theory (EFT) Approach: the top FB asymmetry, longitudinal top polarization, and other observables

### 2.1 Lagrangian

At the Tevatron, the  $t\bar{t}$  production is dominated by  $q\bar{q} \rightarrow t\bar{t}$ , and it would be sufficient to consider dimension-6 four-quark operators (the so-called contact interaction terms) to describe the new physics effects on the  $t\bar{t}$  production at the Tevatron assuming that new physics scale is high enough<sup>4</sup>:

$$\mathcal{L}_6 = \frac{g_s^2}{\Lambda^2} \sum_{A,B} [C_{1q}^{AB} (\bar{q}_A \gamma_\mu q_A) (\bar{t}_B \gamma^\mu t_B) + C_{8q}^{AB} (\bar{q}_A T^a \gamma_\mu q_A) (\bar{t}_B T^a \gamma^\mu t_B)] \quad (2)$$

where  $T^a = \lambda^a/2$ ,  $\{A, B\} = \{L, R\}$ , and  $L, R \equiv (1 \mp \gamma_5)/2$  with  $q = (u, d)^T, (c, s)^T$ . Using this effective lagrangian, we calculate the cross section up to  $O(1/\Lambda^2)$ , keeping only the interference term between the SM and new physics contributions.

We make one comment: the chromomagnetic operators of dim-5 would be generated at one loop level, whereas the  $q\bar{q} \rightarrow t\bar{t}$  operators can be induced at tree level. Therefore the chromomagnetic operators will be suppressed further by  $g_s/(4\pi)^2 \times (\text{loop function})$ , compared with the dim-6 operators we consider in this talk. Therefore we will ignore chromomagnetic operators in this talk.

### 2.2 Origin of FB Asymmetry

It is straightforward to calculate the amplitude for  $q(p_1) + \bar{q}(p_2) \rightarrow t(p_3) + \bar{t}(p_4)$  using the above effective lagrangian and the SM. The squared amplitude summed (averaged) over the final (initial) spins and colors is given by

$$\begin{aligned} |\overline{\mathcal{M}}|^2 \simeq & \frac{4g_s^4}{9\hat{s}^2} \left\{ 2m_t^2 \hat{s} \left[ 1 + \frac{\hat{s}}{2\Lambda^2} (C_1 + C_2) \right] s_\theta^2 \right. \\ & \left. + \frac{\hat{s}^2}{2} \left[ \left( 1 + \frac{\hat{s}}{2\Lambda^2} (C_1 + C_2) \right) (1 + c_\theta^2) + \hat{\beta}_t \left( \frac{\hat{s}}{\Lambda^2} (C_1 - C_2) \right) c_\theta \right] \right\} \end{aligned} \quad (3)$$

where  $\hat{s} = (p_1 + p_2)^2$ ,  $\hat{\beta}_t^2 = 1 - 4m_t^2/\hat{s}$ , and  $s_\theta \equiv \sin \hat{\theta}$  and  $c_\theta \equiv \cos \hat{\theta}$  with  $\hat{\theta}$  being the polar angle between the incoming quark and the outgoing top quark in the  $t\bar{t}$  rest frame. And the

couplings are defined as:  $C_1 \equiv C_{8q}^{LL} + C_{8q}^{RR}$  and  $C_2 \equiv C_{8q}^{LR} + C_{8q}^{RL}$ . Since we have kept only up to the interference terms, there are no contributions from the color-singlet operators with coupling  $C_{1q}^{AB}$ . The term linear in  $\cos \hat{\theta}$  could generate the forward-backward asymmetry which is proportional to  $\Delta C \equiv (C_1 - C_2)$ . Note that both light quark and top quark should have chiral couplings to the new physics in order to generate  $A_{FB}$  at the tree level (namely  $\Delta C \neq 0$ ). This parity violation, if large, could be observed in the nonzero (anti)top spin polarization<sup>5</sup>. We found that the Tevatron integrated top FBA can be explained for  $0.15 \lesssim C_1 \lesssim 0.97$  or  $-0.67 \lesssim C_2 \lesssim -0.15$  at  $1\sigma$  level for  $\Lambda = 1$  TeV. Note that the negative sign of  $C_2$  is preferred at the  $1\sigma$  level. In Fig. 1 (a) and (b), I show the mass dependent top FBA using the ranges of  $C_1$  or  $C_2$  determined from the integrated FBA. Note that the results based on the EFT is somewhat lower than the data at the high  $m_{t\bar{t}}$  region<sup>4</sup>. If this disagreement does not disappear, it would imply that the EFT approach is not a good description for the top FBA.

### 2.3 Longitudinal polarization of top quark probes chiral structures of new physics

The top AFB is not sensitive to the detailed chiral structures of new physics, since the AFB depends on two couplings,  $C_1 = C_{8q}^{LL} + C_{8q}^{RR}$  and  $C_2 = C_{8q}^{LR} + C_{8q}^{RL}$ , and not individual  $C_{8q}^{AB}$ 's. In Ref.<sup>5</sup>, the top longitudinal polarization was proposed as a probe of chiral structures of new physics that would be relevant to the Tevatron top FBA. Note that the longitudinal polarizations of  $t$  and  $\bar{t}$  vanish in QCD due to its parity conservation. Any new physics for the top FBA involve chiral couplings of a new particle to the SM quarks and the parity will be no longer conserved when interfering with QCD.

Neglecting the transverse polarizations, one can derive

$$|\overline{\mathcal{M}}|^2 = \frac{g_s^4}{\hat{s}^2} \left\{ \mathcal{D}_0 + \mathcal{D}_1(P_L + \bar{P}_L) + \mathcal{D}_2(P_L - \bar{P}_L) + \mathcal{D}_3 P_L \bar{P}_L \right\}. \quad (4)$$

where  $P_L$  and  $\bar{P}_L$  are the longitudinal polarizations of  $t$  and  $\bar{t}$ . The unpolarized coefficient  $\mathcal{D}_0$  leads to the total cross section  $\sigma_{t\bar{t}}$  and the forward-backward asymmetry  $A_{FB}$  shown in Eq. (3). On the other hand, the coefficient  $\mathcal{D}_3$  gives the spin-spin correlations  $C$  and  $C_{FB}$  considered and suggested in Ref.<sup>5</sup>.

Note that the other two coefficients  $\mathcal{D}_1$  and  $\mathcal{D}_2$  are  $P$  violating. Furthermore, the coefficient  $\mathcal{D}_1$  is odd under both the CP and  $\widetilde{\text{CPT}}$  transformations<sup>a</sup>. In our effective lagrangian approach, new heavy particles are integrated out, and there is no new strong CP-even phase, and so  $\mathcal{D}_1$  is zero. However, it could be nonzero when the heavy particle is explicitly included, and we keep the finite decay width of the heavy particle together with possible CP-violating phases in its couplings to light and top quarks. This issue will be discussed in full in the future publication<sup>8</sup>.

The other  $P$ -violating coefficient  $\mathcal{D}_2$  could be observable at the Tevatron, revealing genuine features of new physics responsible for  $A_{FB}$ . Explicitly, we have obtained

$$\mathcal{D}_2 \simeq \frac{\hat{s}}{9\Lambda^2} \left[ (C'_1 + C'_2) \hat{\beta}_t (1 + c_{\hat{\theta}}^2) + (C'_1 - C'_2) (5 - 3\hat{\beta}_t^2) c_{\hat{\theta}} \right] \quad (5)$$

with  $C'_1 \equiv C_{8q}^{RR} - C_{8q}^{LL}$ ,  $C'_2 \equiv C_{8q}^{LR} - C_{8q}^{RL}$ . Therefore  $\mathcal{D}_2$  will provide additional information on the chiral structure of new physics in  $q\bar{q} \rightarrow t\bar{t}$ . When we integrate over the polar angle  $\hat{\theta}$ , only the first term involving  $(C'_1 + C'_2) = C_{8q}^{RR} - C_{8q}^{LL} + C_{8q}^{LR} - C_{8q}^{RL}$  survives. On the other hand, if we separate the forward and the backward top samples and take the difference, the orthogonal combination in the second term survives:  $(C'_1 - C'_2) = C_{8q}^{RR} - C_{8q}^{LL} - C_{8q}^{LR} + C_{8q}^{RL}$ .

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<sup>a</sup>The  $\widetilde{\text{T}}$  transformation reverses the signs of the spins and the three-momenta of the asymptotic states, without interchanging initial and final states, and the matrix element gets complex conjugated.

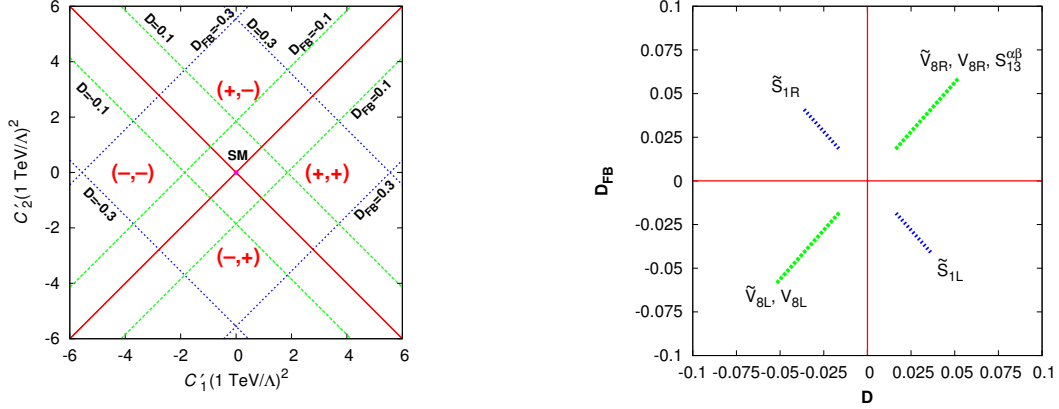


Figure 2: The  $P$ -violating spin correlations  $D$  and  $D_{FB}$  in the  $(C'_1, C'_2)$  plane. The signs of  $(D, D_{FB})$  are denoted.

For definiteness, we consider the two new observables:

$$D \equiv \frac{\sigma(t_R \bar{t}_L) - \sigma(t_L \bar{t}_R)}{\sigma(t_R \bar{t}_R) + \sigma(t_L \bar{t}_L) + \sigma(t_L \bar{t}_R) + \sigma(t_R \bar{t}_L)},$$

$$D_{FB} \equiv D(\cos \hat{\theta} \geq 0) - D(\cos \hat{\theta} \leq 0) \quad (6)$$

which involve the sum and difference of the coefficients  $C'_1$  and  $C'_2$ , respectively. In Fig. 2, we show the  $P$ -violating spin correlations  $D$  and  $D_{FB}$  in the  $(C'_1, C'_2)$  plane within the parameter region consistent with the top FBA at the Tevatron. We observe that  $|D|$  and  $|D_{FB}|$ , which are zero in the SM, could be as large as 0.1 in the region  $|C'_{1,2} (1 \text{ TeV}/\Lambda)^2| \lesssim 1$ , which have to be actively searched for.

### 3 Beyond the EFT : the case of extra $Z'$ model with flavored multi Higgs Doublets

#### 3.1 Original $Z'$ model for the top FBA

Now let us consider an explicit model, a  $Z'$  model first proposed by Jung, Murayama, Pierce and Wells<sup>3</sup>. In this model, it is assumed that there is a flavor changing couplings of  $Z'$  to the right-handed  $u$  and  $t$  quarks:

$$\mathcal{L} = -g_X Z'_\mu [\bar{t}_R \gamma^\mu u_R + H.c.]. \quad (7)$$

The  $t$ -channel exchange of  $Z'$  leads to the Rutherford peak in the forward direction and generates the desired amount of the top FBA if  $Z'$  is around 150 – 250 GeV and  $g_X$  is not too small. Here  $Z'$  is assumed to couple only to the right-handed (RH) quarks in order to evade the strong bounds from the FCNS processes such as  $K^0 - \bar{K}^0$ ,  $B_{d(s)}^0 - \bar{B}_{d(s)}^0$  mixings and  $B \rightarrow X_s \gamma$ . And such a light  $Z'$  should be leptophobic in order to avoid the strong bounds from the Drell-Yan processes. Therefore the original  $Z'$  model is chiral, leptophobic and flavor non universal. It would be nontrivial to construct a realistic gauge theory which satisfies these conditions. Also the original  $Z'$  model was excluded by the same sign top pair productions, because  $Z'$  exchange can contribute to  $uu \rightarrow tt$ .

#### 3.2 $U(1)'$ models with flavored multi Higgs doublets by Ko, Omura and Yu

In Ref.s<sup>6,7</sup>, realistic models for such peculiar  $Z'$  have been constructed, and were shown to be less constrained by the same sign top pair production. In Ref.s<sup>6,7</sup>,  $Z'$  is assumed to be a

gauge boson of a new  $U(1)'$  local gauge symmetry, under which the RH quarks are charged non universally, whereas other quarks are charged universally or completely neutral. Then one cannot write renormalizable Yukawa couplings to the RH up-type quarks, since  $\overline{Q}_L \tilde{H} u_R$  is not gauge invariant, where  $H$  is the SM Higgs doublet which is  $U(1)'$  singlet and generates masses for the down-type quarks and charged leptons. We have to introduce new Higgs doublets  $H_i$  which are charged under the new  $U(1)'$ . We can also introduce a singlet scalar which carries  $U(1)'$  charge and breaks  $U(1)'$  spontaneously. However it is not mandatory to introduce  $\Phi$ , since the newly introduced  $U(1)'$ -charged Higgs doublets  $H_i$  also break  $U(1)'$  and generate  $Z'$  mass too. The offshot of the chiral  $Z'$  model is that one has to extend the Higgs sector, whether  $Z'$  couplings are flavor universal or not, as long as the  $Z'$  couplings are chiral.<sup>b</sup> The same arguments apply to other models with new spin-1 objects that have chiral couplings to the SM fermions, including the axigluon, extra  $W'$ ,  $SU(2)$   $W_I$ ,  $Z_I$  and  $SU(3)_R$  flavor gauge bosons.

Introducing  $U(1)'$  flavored Higgs doublets is very important because they generate nonzero top mass. They also play an important role in top FBA phenomenology. For example the Yukawa couplings of the neutral scalar bosons  $h, H, a$  have flavor changing couplings to the up-type quarks because of the flavor non universal nature of  $Z'$  interaction<sup>6,7</sup>:

$$Y_{tu}^h = \frac{2m_t(g_R^u)_{ut}}{v \sin(2\beta)} \sin(\alpha - \beta) \cos \alpha_\Phi, \quad (8)$$

$$Y_{tu}^H = -\frac{2m_t(g_R^u)_{ut}}{v \sin(2\beta)} \cos(\alpha - \beta) \cos \alpha_\Phi, \quad (9)$$

$$Y_{tu}^a = \frac{2m_t(g_R^u)_{ut}}{v \sin(2\beta)}. \quad (10)$$

These Yukawa couplings are not present in the Type-II 2HDM, for example. Our models proposed in Ref.s<sup>6,7</sup> are good examples of non minimal flavor violating multi Higgs doublet models. The top FBA and the same sign top pair productions are generated not only by the  $t$ -channel  $Z'$  exchange, but also by the  $t$ -channel exchange of neutral Higgs scalars, and the strong constraint on the original  $Z'$  model from the same sign top pair production can be relaxed by a significant amount. The results with a few low lying (pseudo)scalar bosons as well as  $Z'$  are shown in Fig. 3. Note that the strong bound from the same sign top pair production can be evaded because of the  $t$ -channel exchanges of  $h$  and  $a$ . And the  $m_{t\bar{t}}$  distribution becomes closer to the SM case in the presence of  $h$  and  $a$  contributions. (See Ref.<sup>7</sup> for more detailed discussions on top charge asymmetry at the LHC and Ref.<sup>9</sup> for the  $B$  physics constraints on these models.)

## 4 Conclusions

In this talk, I discussed two independent approaches for the top FB asymmetry observed at the Tevatron in the framework of new physics models beyond the SM. Whatever the new physics solutions may be, there are some common features: we need new interactions with chiral couplings to the top and the light quarks, and nontrivial flavor structures in the quark sector, which is not easy to achieve in any realistic models because of the strong constraints from  $K$  and  $B$  meson systems. If the new physics involves chiral couplings of new spin-1 vector boson, one has to extend the Higgs sector too, by including new Higgs doublets that couple to the new spin-1 vector boson. Otherwise, the model cannot give the up-type quark masses. All the top-related observables we are interested in, such as top FB asymmetry at the Tevatron, the same sign top pair production cross section and top charge asymmetry at the LHC, are crucially dependent on the extended Higgs sector as well as the spin-1 objects with chiral couplings, and it is meaningless to discuss the phenomenology without the new Higgs doublets.

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<sup>b</sup>The model has gauge anomaly, and one has to add some fermions. This issue is described in Ref.<sup>6</sup> in detail.

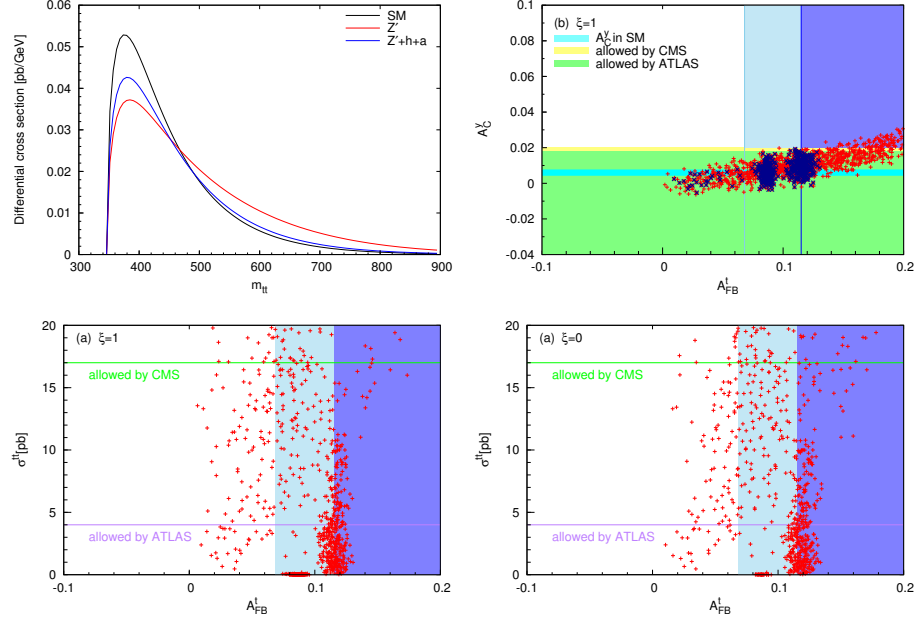


Figure 3: The scattered plots for (a) the  $m_{t\bar{t}}$  distributions for the SM, SM+ $Z'$  and SM +  $Z', h + a$ , (b)  $A_{\text{FB}}^t$  at the Tevatron and  $\sigma^{t\bar{t}}$  at the LHC for  $\xi = 1$ , and (c) and (d)  $A_{\text{FB}}^l$  at the Tevatron and the charge asymmetry  $A_C^y$  at the LHC for  $\xi = 1$  and  $\xi = 0$ , respectively.

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## References

1. J. H. Kuhn and G. Rodrigo, arXiv:1109.6830 [hep-ph]
2. T. Müller, plenary talk at the ICHEP2012, Melbourne, Australia
3. S. Jung, H. Murayama, A. Pierce and J. D. Wells, *Phys. Rev. D* **81**, 015004 (2010)
4. D.-W. Jung, P. Ko, J. S. Lee and S.-h. Nam, *Phys. Lett. B* **691**, 238 (2010); D.-W. Jung, P. Ko and J. S. Lee, *Phys. Lett. B* **708**, 157 (2012)
5. D.-W. Jung, P. Ko and J. S. Lee, *Phys. Lett. B* **701**, 248 (2011) ; *Phys. Rev. D* **84**, 055027 (2011)
6. P. Ko, Y. Omura and C. Yu, *Phys. Rev. D* **85**, 115010 (2012) ; *JHEP* **1201**, 147 (2012)
7. P. Ko, Y. Omura and C. Yu, arXiv:1205.0407 [hep-ph], to appear in EPJC
8. D.-W. Jung, P. Ko and J. S. Lee, work in progress
9. P. Ko, Y. Omura and C. Yu, KIAS Preprint P12084, arXiv:1212.4607 [hep-ph]